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## **PERSONNEL PHYSICAL ACTIVITY LEVELS ON NAVAL VESSELS - EVIDENCE FOR SOPORIFIC AND FATIGUE EFFECTS?**

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### **ABSTRACT**

Among the factors contributing to performance decrements at sea, sopite syndrome and motion induced fatigue are elusive but of considerable interest. The present work attempts to quantify these effects by evaluating the decrease of personnel physical activity while underway. Activity evaluation was based on actigraphy data, an approach used previously on a high speed catamaran, FSF-1 Sea Fighter, although the seas were calm resulting in little motion influence. The present work extends this approach by analyzing crew activity decrease during significant sea states on two high speed vessels, HSV-2 SWIFT (19 participants, 8-day period), and again on the FSF-1 Sea Fighter (13 participants, 12-day period). During the data collection periods, personnel were conducting their normal duties in sea states ranging from 3 to 6.

Actigraphy data showed that physical activity was inversely related to ship motion / sea state, with activity depicting a logarithmic decrease with higher provoking motions on both naval vessels (HSV-2:  $F(1,10)=5.61$ ,  $p=0.039$ ,  $R^2=0.36$ ; FSF-1:  $F(1,5)=3.45$ ,  $p=0.12$ ,  $R^2=0.41$ ), and on the combined population of data ( $F(1,17)=14.8$ ,  $p=0.001$ ,  $R^2=0.47$ ). We suggest the possibility that these reductions in personnel activity levels may be evidence of some combination of sopite syndrome and motion induced fatigue. Although crew activity changes reflect mission requirements, the observed decline in activity may be a step towards quantifying the task-related and operational effects of sopite syndrome and motion induced fatigue.

*Keywords: physical activity, actigraphy, sopite syndrome, fatigue*

### **1. INTRODUCTION**

As Colwell [1989] noted "...the goal of work on human performance in the naval environment is to develop methods and criteria which permit quantitative analysis of human performance and its degradation due to motion-induced problems." Unfortunately, this quantitative analysis poses a significant research challenge because the naval operational environment is a complex, dynamic, and time variant system where the efficacy of the numerous stressors (both individually or through their interactions) on the humans is complicated (and in general may act both ways, positively or deleteriously).

Although there is a significant volume of research literature on human performance at sea [Colwell, 1989; Hettinger, Kennedy, & McCauley, 1990; Smith, Allen, & Wadsworth, 2006; Stevens & Parsons, 2002; Wertheim, 1998], there are still gaps in existing knowledge [Colwell, 2005]. These gaps are evident in the human performance standards related to ship design [Matsangas, McCauley, & Papoulias, 2009]. Research is needed to better understand the effects of sopite syndrome, motion induced fatigue, and the

association between sleep disturbances and ship's motion [Grow & Sullivan, 2009].

While underway, naval personnel performance may be affected by a number of stressors such as physical fatigue due to task activities, sleepiness, motion induced fatigue, motion sickness, and sopite syndrome. It is expected that one or more of these factors may lead to lethargy and decreased physical activity levels of personnel due to these stressors. Johnston [2009] suggested that decreased crew activity levels, based on actigraphy measures, could be an indicator of sopite syndrome. He hypothesized that crew activity levels while awake would be inhibited by ship's motion and the consequent soporific effects. His findings supported his hypothesis-- there was a significant decrease in crew activity related to days underway. To evaluate personnel activity he used a new measure derived from personnel actigraphic recordings. Actigraphy is a validated method for the evaluation of sleep attributes [Ancoli-Israel et al., 2003; Caldwell & Caldwell, 1993; Mullaney, Kripke, & Messin, 1980], and has been used extensively in operational sleep studies at Naval Postgraduate School [Mason, 2009; McCauley, Matsangas, & Miller, 2005; McCauley et al., 2007; N. L. Miller & Shattuck, 2005; N. L. Miller, Shattuck,

Matsangas, & Dyche, 2008]. But, actigraphy has not, to our knowledge, been used previously to measure waking activity levels.

Based on Johnston's work [2009], the present study will: a) further evaluate the possible relation between ship's motion and personnel physical activity in environments with provoking motions, b) extend his initial approach by refining the measurement methodology.

## **2. METHODOLOGY**

The present paper is based on a retrospective analysis of existing actigraphic recordings from two earlier studies in the naval operational environment, one conducted on the HSV-2 SWIFT, and one on FSF-1 Sea Fighter.

The HSV-2 SWIFT data were collected from 10 – 23 May 2004 while she was transiting from Kristianstad, Norway to Norfolk, Virginia and executing seakeeping trials [McCauley et al., 2005]. Nineteen crew members of HSV-2 SWIFT took part in the study; 18 were male and 1 was female. The operational profile of the SWIFT during the first seven days was not normal. Rather than avoiding large seas, she sought them out. Rather than reducing speed upon encountering large seas, she maintained relatively high speed (>30 knots) and performed octagon maneuvers. Ship's motion was assessed by the Naval Surface Warfare Center, Carderock Division, as part of a seakeeping evaluation of the HSV-2 SWIFT [Bachman, Woolaver, & Powell, 2004].

The data collection period on the FSF-1 Sea Fighter spanned a 7-day period in March 2007, while the ship was transiting from San Diego to the Panama Canal zone [McCauley et al., 2007]. The study involved 24 participants, either civilians, military or contracted crew members. Ship's motion was assessed by a data acquisition system designed by Naval Surface Warfare Center – Panama City. Sea state was determined using the Sea Fighter's TSK Wave Height Meter, which collected Significant Wave Height (the average wave height of the one-third highest waves of a given wave group - SWH) and Dominant Wave Period (the period of the waves with maximum energy - DWP).

Apparatus for both studies included wrist activity monitors (WAMs; Actiwatch by Minimitter, Bend, OR), and individual sleep and activity logs contained in booklets. WAMs are wrist-worn devices containing an accelerometer that records motion. When worn continuously or during sleep periods, the WAMs provide reliable estimates of sleep duration and

quality. The WAMs detect motion in the frequency range between 3 and 11 Hz by sampling at 32 Hz, with the internal accelerometer sensitivity being 0.05 g. With each movement of the hand/arm, the accelerometer generates a variable voltage that is digitally processed, integrated over a user-selected epoch, and expressed as an "Activity Count" value that is recorded for subsequent download and analysis.

Analysis of actigraphy data was based on awake periods' activity excluding sleep, resting, and WAM off periods. These data were then averaged over daily intervals.

Research from the use of actigraphy on high speed unconventional ship designs has indicated that ship's motion may have an effect on Actiwatch WAM output [N. Miller, McCauley, & Matsangas, 2005]. For the purpose of overcoming this issue, WAMs were firmly fastened on bulkheads of both ships, at personnel living spaces. These WAMs were used for identifying periods of significant ship's motion interference on WAMs worn by the participants.

In accordance with the NPS IRB policy, the signed consent forms in both studies acknowledged that the participants were volunteers, fully understood the nature of the study, the confidentiality of the data, and were free to discontinue participation at any time without consequence.

## **3. SHIP MOTION AND CREW MOTION**

Ship motion data were collected from wave height measuring systems [McCauley et al., 2005; McCauley et al., 2007], and activity data from an actiwatch affixed to a bulkhead near the galley (forward, on longitudinal centerline) [McCauley et al., 2005]. The latter was initially used to determine if the HSV-2 motion affected the activity data recorded by the WAMs worn by the study participants. Analysis of the strapped WAM activity showed that the detected activity was significantly related to motion sickness and reports of motion induced interruptions (for more information refer to the technical report [McCauley et al., 2005]). Furthermore, strapped WAM activity was found to be related to the measured significant wave height [McCauley & Matsangas, 2005]. These observations on HSV-2 showed that motion detected by the affixed WAM could be used as an estimator of the overall severity of motion imparted to the humans onboard the ship, albeit not in a precise manner. Detailed correlation analysis had shown, in previous analyses, that the ship's motion activity (SMA), when smoothed with an exponential function taking into

account the average activity over 30-minute intervals (SMA-30), was significantly related to human motion sickness severity and motion induced interruptions on the HSV-2 [McCauley & Matsangas, 2005; McCauley et al., 2005].

On the other hand, the use of a WAM as a motion detection and evaluation apparatus is controversial for a number of good reasons. The first is related to the bandwidth of the given apparatus which ranges from 3 to 11 Hz, a constrained spectrum given the envelope of motions affecting the human (for a comparison, ISO 2631-1 notes that motion should be assessed in the frequency range between 0.1 and 80 Hz [ISO, 1997]). Nevertheless, on a naval vessel, this 3 to 11 Hz envelope includes a substantial amount of the energy projected to the human, given that higher frequencies include decreased energy. Concerns are found not only in the use of a WAM as a motion detection device, but also in the use of significant wave height (SWH). Given that this study is concerned with the efficacy of motion induced to the human, SWH is only one of the factors that should be taken into account. The ship is acting as a low pass filter according to ship's Response Amplitude Operators (RAO), which describe the ship's response to unit-amplitude waves in each component direction and her motion depends on wave height, period, ship's speed and the relative angle between the ship's course and wave direction. The existence of waves from multiple directions further complicates the overall problem

Therefore, even SWH cannot be considered to be a tidy metric for the needed ship motion data. Given the aforementioned metric difficulties, motion evaluation in this preliminary work will be based on both the significant wave height (SWH), and the 30-minute interval WAM activity average (SMA-30).

#### 4. RESULTS

First, we will address the results from HSV-2. The 12-day data collection period included one underway period, but during the first seven days the ship conducted sea-keeping trials. These trials included high speed steaming in octagon patterns, therefore there was an increased level of ship's motion. These atypical maneuvers cannot be observed on SWH but only on SMA-30, because motion detected by the actiwatch is related to the combination of sea state characteristics (SWH, wave period) and ship's speed/relative heading. Another issue of interest is that the level of personnel activity showed a large inter-subject variability; therefore it depends heavily on the person involved. In order to overcome this issue, we

calculated the percentage-wise activity level for each participant. The activity level of the first underway day was considered as the baseline level. This transformation is given by the following equation.

$$Activity_{\%,i,j} = \frac{Activity_{i,j}}{Activity_{1,j}}$$

In this equation  $Activity_{\%,i,j}$  is the mean daily percentage-wise activity level of participant  $j$  during underway day  $i$ ,  $Activity_{i,j}$  is the mean daily activity level of participant  $j$  during underway day  $i$ , and  $Activity_{1,j}$  is the mean daily activity level of participant  $j$  during the 1st underway day. Based on  $Activity_{\%,i,j}$ , we further calculate  $Activity_{\%,i}$ , which refers to the mean daily percentage-wise activity level for underway day  $i$ .

$$Activity_{\%,i} = \frac{\sum_{j=1}^n Activity_{\%,i,j}}{n}$$

In this equation  $n$  refers to the total number of participants in the study. This percentage-wise activity level  $Activity_{\%,i}$  is used in the analysis depicted hereafter.

The following figure depicts the time evolution of personnel activity on a daily basis. Motion data were based on the Significant Wave Height (SWH), the corresponding Sea State according to Pearson-Morskowitz, and the motion detected by the actiwatch strapped on a bulkhead of the ship.

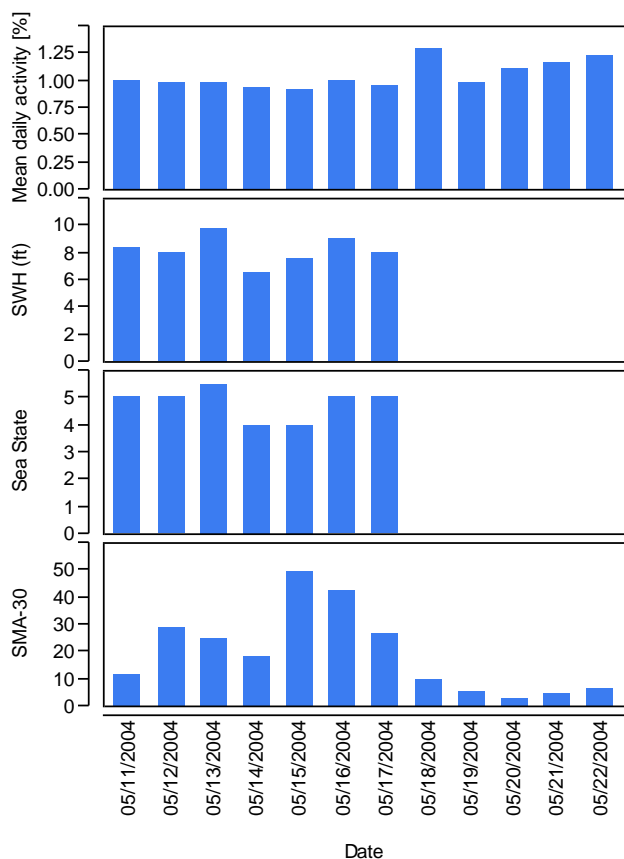


Figure 1: Activity and motion vs time on HSV-2 SWIFT

The SWH data were available only for the first seven days underway, and even during these days, sea state varies only  $\pm 14\%$  (excluding the fourth day). Therefore, by using only SWH we omit from further analysis five more days of useful data, and it becomes more difficult to derive useful information regarding the effect of motion on activity (mainly because of the non-linearity of such phenomena). For this reason, SMA-30 (actigraphy derived motion) will be used instead of the SWH data. The other interesting point from the above figure is the significant increase in crew activity at the 8<sup>th</sup> day and during the last three days of the underway leg. The increase during the 8<sup>th</sup> day might be related to two factors, the lower induced motion depicted in SMA-30, and the fact that this was the first day underway after seven days of sea-keeping trials. The sea trials included periods of significantly provoking motions (inducing nausea and interruption of tasks), therefore a possible explanation for this increase in activity might be related to the need to deal with tasks that were deferred during rough ship motions. On the other hand, the activity increase during the last three days may be attributed to reduced ship motions as well as other physical activity trends yet to be

identified (for example, personnel dealing with tasks that needed to be accomplished before the ship reaching her final destination, or other).

Analysis showed that activity levels in this data set were not associated to the days underway, but to the severity of induced motion. By using SMA-30 as the motion metric (in order to analyze the activity change during all 12 days of the underway leg), it is concluded that personnel mean daily activity in this data set depicts a logarithmic decrease related to ship's motion ( $F(1,10)=5.61$ ,  $p=0.039$ ,  $R^2=0.36$ ) given by the following equation.

$$Activity_{\%} = 1.2437246 - 0.0782446 * \text{Log}(SMA-30)$$

An association between SMA-30 and the standard deviation of daily activity also was identified. These results are depicted on the following figure.

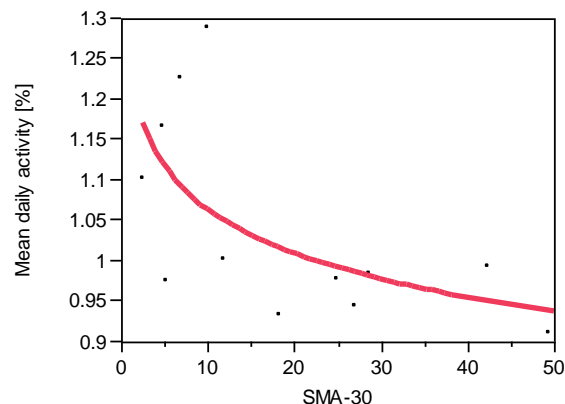


Figure 2: Mean daily activity level vs induced motion on HSV-2 SWIFT

The next step of this analysis is focused on the results from FSF-1. The following figure depicts the time evolution of personnel activity on a daily basis during the 7-day data collection period. Motion data were based on the Significant Wave Height and the corresponding Sea State according to Pearson-Morskowitz.

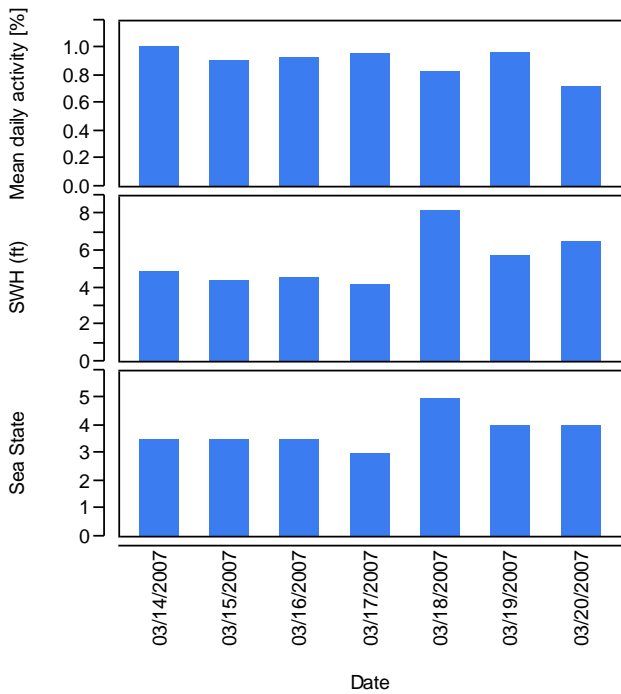


Figure 3: Activity and motion vs time on FSF-1

By using SWH (in feet) as the motion metric (in order to analyze the activity change during all seven days of the underway leg), it is concluded that personnel mean daily activity in this data set depicts a logarithmic decrease related to ship's motion ( $F(1,5)=3.45$ ,  $p=0.12$ ,  $R^2=0.41$ ) given by the following equation.

$$Activity_{\%} = 1.327601 - 0.2555029 * \text{Log}(SWH)$$

An association also was found between SWH (in feet) and the standard deviation of daily activity ( $F(1,4)=7.82$ ,  $p=0.05$ ,  $R^2=0.66$ ), with more severe wave height linearly related to increased variability in crew activity levels.

These results are depicted on the figures 4 and 5.

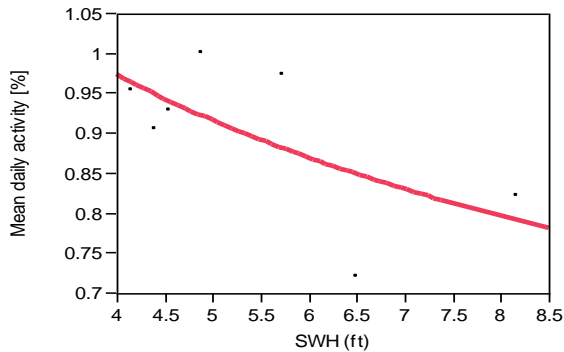


Figure 4: Mean daily activity level vs induced motion on FSF-1

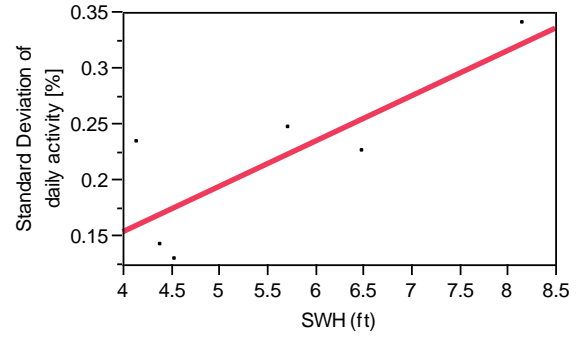


Figure 5: Standard deviation of daily activity level vs induced motion on FSF-1

The final step in this analysis was to address the effect of motion on mean daily activity when the populations are integrated into one. The challenge with this approach is that we have different motion measures from the two studies. From HSV-2 we use actigraphy-derived motion (in order to use all underway days) and from FSF-1 we have SWH. In order to combine the two motion metrics we first normalized motion data independently for each ship. Normalization included dividing each day's motion by the max motion observed during the underway leg. This process was conducted by the following equation.

$$Motion_{\%,i} = \frac{Motion_i}{Motion_{MAX}}$$

In this equation  $Motion_{\%,i}$  is the mean daily percentage-wise motion level during underway day  $i$ ,  $Motion_i$  is the mean daily motion level during underway day  $i$ , and  $Motion_{MAX}$  is the maximum mean daily motion of all underway days.

This approach for combining different motion levels focuses merely on the subjective impact of motion on the human, and how human performance changes depending on induced motion changes. One methodological challenge for evaluating human response to induced motion is that one should be able to measure motion at the point of contact to the human body (as noted in the appropriate standards for addressing motion effects [BSI, 1987; ISO, 1997]). In one of the two studies described here, crew members moved freely about the vessel, obviating the opportunity to measure ship motion input to each individual. Therefore, SWH is just one, essentially generic, metric of motion and not an index of motion input to any individual.



Using this approach, we pooled the two data sets. Analysis showed that the effect of motion on activity was again significant ( $F(1,17)=14.8$ ,  $p=0.001$ ,  $R^2=0.47$ ) given by the following equation.

$$Activity_{\%} = 0.8875 - 0.1033 * \text{Log}(\text{Induced Motion})$$

These results are depicted on the following figure.

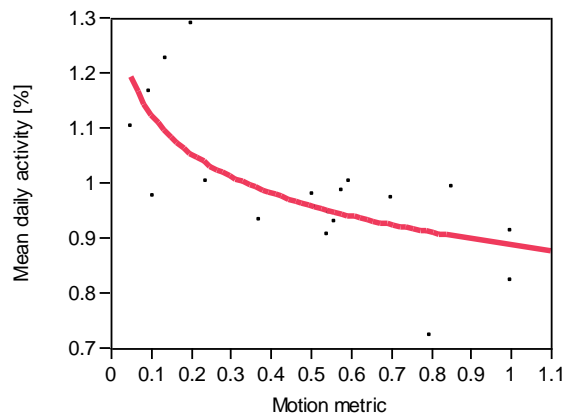


Figure 6: Mean daily activity level versus induced motion

## 5. DISCUSSION

The assessment of personnel physical activity in the operational environment poses a significant challenge given that the personnel are dealing with assigned tasks or duties, and there are a number of stressors simultaneously affecting shipboard personnel. Johnston's (2009) approach of using actigraphy to evaluate activity (or lethargy) while awake is a useful, non-invasive method of assessing human behavior patterns. However, the implementation of this approach raises a number of concerns.

The use of WAMs to measure motion per se is the first and foremost issue. WAMs are simple, omnidirectional accelerometers that provide an activity count rather than a level of acceleration. Therefore, they detect the combination of all external motions, human-generated or ship-induced. Furthermore, the activity measured by the WAM is the activity detected at the non-dominant hand and the frequency range between 3 and 11 Hz.

On the other hand, the external validity also is at risk because, even without the deleterious effect of motion, personnel activity depends on the duties assigned, the specific tasks involved, and the timing of the tasks during the underway leg. In general, the

initial and final parts of the underway phase are expected to be more active. Therefore, some of the change in activity may be attributed to the combination of sea state and time underway.

The final and most important issue is what, exactly, are the actiwatches detecting? Is the decrease in personnel activity an effect of motion induced fatigue, sopite syndrome, or sleep deprivation, or some combination? It is interesting to observe that sleep deprivation was found in both studies included herein [McCauley et al., 2005; McCauley et al., 2007], albeit it was not clear in Johnston's [2009] because of lack of sleep logs.

Given that sea state was not significantly provoking nausea, the systematic decline in crew physical activity that Johnston found suggests that other significant stressors such as sopite syndrome and possibly motion induced fatigue (MIF) ) accumulating by time may have contributed to the trend (although MIF was not evaluated in his work). Sopite syndrome is a set of motion-originated symptoms associated with lethargy, drowsiness, and disinclination for work [Graybiel & Knepton, 1976].

On the other hand, the present analysis showed a second systematic trend, where personnel activity is inversely associated with the severity of induced motion. The possible causality between motion and activity, or even a detailed analysis of the attributes of this activity change, cannot be established with the current data. Nevertheless, it is evident from the three data sets used in this work that naval personnel become less active while underway. So far, we have evidence that this reduction in activity may be attributed to the number of days underway and to the severity of provocative (induced) motion.

Given the nature of the three data sets used in this work, the reasons underlying the observed systematic reduction in activity cannot be identified. The corresponding research literature of personnel performance at sea proposes that there is a significant number of potential stressors that may be involved, occupational, environmental, etc [Comperatore, Rivera, & Kingsley, 2005; Oldenburg, Jensen, Latza, & Baur, 2009]. Among others, the perceived major stressors associated with work performance at sea are known to be fatigue related to sleep deprivation and disturbances, motion induced fatigue, motion sickness (including sopite syndrome effect [Graybiel & Knepton, 1976]), and biodynamic problems [Smith et al., 2006]. The following list includes a taxonomical integration of the major factors that can have an effect of the physical activity levels of personnel while underway.

- Occupational
  - Assigned duties and activities, timing of tasks, etc
- Non-occupational
  - Environmental
    - Motion
      - Motion sickness
      - Sopite syndrome
      - Motion induced fatigue
    - Sleep disturbances
  - Psychological

Revisiting the analysis of the three data sets used in this work, reveals that some of these factors were involved, [Johnston, 2009; McCauley et al., 2005; McCauley et al., 2007]. Nevertheless, these data sets are derived from studies that were not originally focused on personnel activity levels, therefore no conclusions can be made about the degree that these factors have affected or contributed to the observed reduction in activity. By taking into account the existing literature, and the results of our analyses, we can only derive a “possible” association. The following table gives a brief overview of these thoughts.

**Table 1: Factors probably involved in personnel decreased activity (a tickmark denotes a possible effect)**

Factors	HSV-2 [McCauley et al., 2005]	FSF-1 [McCauley et al., 2007]	FSF-1 [Johnston, 2009]
Sleep deprivation	✓	✓	NA
Motion induced fatigue	✓	✓	✓
Motion sickness/ Sopite syndrome	✓	✓	✓
Biodynamic interference	✓	✓	

## 6. CONCLUSIONS

Evidence from this analysis, combined with Johnston’s [2009] findings, support the conclusion that personnel activity level while underway depicts two distinct patterns of degradation, one related to days underway (more evident when motion is not significantly provoking), and one related to provoking motion. Although others stressors possibly associated to physical activity levels do exist, this analysis on two

data sets (HSV-2, FSF-1) shows that provocative motion accounts for 36% to 41% of the observed variability. Our evidence, based on the retrospective analysis of three data sets, is an initial approach to this phenomenon of personnel activity reduction. Future work will focus on analyzing multiple data sets with various levels of motion severity in order to validate the existence of the processes of activity reductions due to provocative motion, and days underway, identify possible interaction between these two variables, and to develop an appropriate mathematical model. Attention also will be focused on how the tasks assigned to personnel are related to daily activity variability, an issue that could not be addressed in the existing data sets.

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